IEEE-1588 STANDARD FOR A PRECISION CLOCK SYNCHRONIZATION PROTOCOL FOR NETWORKED MEASUREMENT AND CONTROL SYSTEMS AND APPLICATIONS TO THE POWER INDUSTRY

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Introduction:

Electronic measurement and control systems are found throughout modern power systems. These measurement and control systems typically involve the exchange of information between one or more controllers and numerous IEDs. Correct operation of these systems requires that the temporal relationships between sensor reading, time tagging, and controller computations be synchronized. Synchronization requirements are dictated by the kinds of correlations and analysis to be applied to the data, the parameters of the control loops, the characteristics of the plant under control, and the overall system accuracy requirements.

This paper discusses the implementation of synchronization in power system measurement and control systems and the potential role of IEEE 1588 in this implementation.

Traditionally these systems have been implemented with proprietary or industry specific computation, synchronization, and communication protocols and techniques. In recent years the industry has started to use technologies and components developed for the general computing environment. Cost, bandwidth and ease of use have been the driving forces behind this trend.

This trend is reflected in ongoing standards work. For example, based on the work first initiated by the Electrical Power Research Institute under Research Project 3599, IEEE P1525 specifies communications based on TCP/IP and UDP/IP in an Ethernet LAN environment. IEC 61850 takes a similar approach. Both also exploit technologies developed in the general computing environment for data handling, configuration, etc. including object models, XML, ASN.1 and others.

Synchronization requirements in the general computing environment are typically measured in milliseconds to seconds and are dictated by applications such as distributed file systems, financial transactions, and office computing applications. Many of the world's networked computers synchronize their clocks using the popular Network Time Protocol, NTP, which operates over Ethernet based LANs and the wide area protocols constituting the Internet, [NTP].

In the power industry, typical synchronization specifications for protection and control systems range from milliseconds for time tagging breaker operations and other events to one microsecond for synchrophasor measurements, as defined in IEEE 1344 Standard for Synchrophasors for Power Systems [1344]. These tighter synchronization requirements must be met in computing, network, and operating environments that differ from those in a general computing environment. IEEE 1588 was designed with these tighter requirements in mind.

Measurement and control techniques using synchronized clocks:
There are three distinct architectures for implementing synchronization in distributed systems. Each has found application areas to which it is well suited.

1. Message-based timing. In this architecture the timing of an action or the presumed time of sampling of a datum is based on the receipt of the message carrying the information. This style of timing or synchronization is essentially the only one used in traditional laboratory or other instrumentation system applications based on IEEE-488. In power systems any direct command sent to a device and executed on receipt fits this model.
2. Cyclic-timing. In this architecture the timing of actions and data sampling is periodic. The period is usually established by the communication system linking the components. This architecture is widely used in the motion control industry with the timing established by the SERCOS bus.
3. Time-based. In this third architecture, timing is based directly on a common sense of time. In power systems this common sense of time is currently established in one of two ways. SCADA protocols provide a means for the master station to set clocks in remote terminal units (RTUs), but only to an accuracy of several milliseconds. When more precise clock setting is required, it is achieved by the use of GPS receivers for each site and intra-site distribution of time using a timing bus. IEEE 1588 is designed to facilitate the implementation of time-based architectures.

While all three styles have applications to which they are best suited, the remainder of this discussion will focus on time-based systems.

With the move to protocols and components developed for the general computing environment, it is desirable to establish this common sense of time using the LAN to avoid additional wiring and equipment. Properly implemented, this common sense of time will appear to applications as part of the infrastructure along with network communications, file systems, etc. The presence of a common sense of time will allow the timing of events to be more decoupled from communication latency issues and application execution issues than is typical in today's systems.

A typical time-based measurement and control system using Ethernet for network communications is illustrated in Figure 1. Each Intelligent Electronic Device (IED) contains a clock, synchronized to its peers, to establish a common sense of time throughout the system. How IEEE 1588 produces this synchronization will be discussed later. The system is shown as a hierarchical system in which IEDs communicate directly to an Ethernet switch or repeater. Switches and repeaters can be further aggregated to form subnets defined by an Ethernet router. In a power system environment, it is quite likely that the links would use fiber optics for electrical isolation and noise immunity and that some form of redundancy, not shown, would be used. The IEDs can be sensors, actuators, controllers, or any other networked electronic device. Typically there will be one or more central controllers or substation computers near the top of the hierarchy as shown.

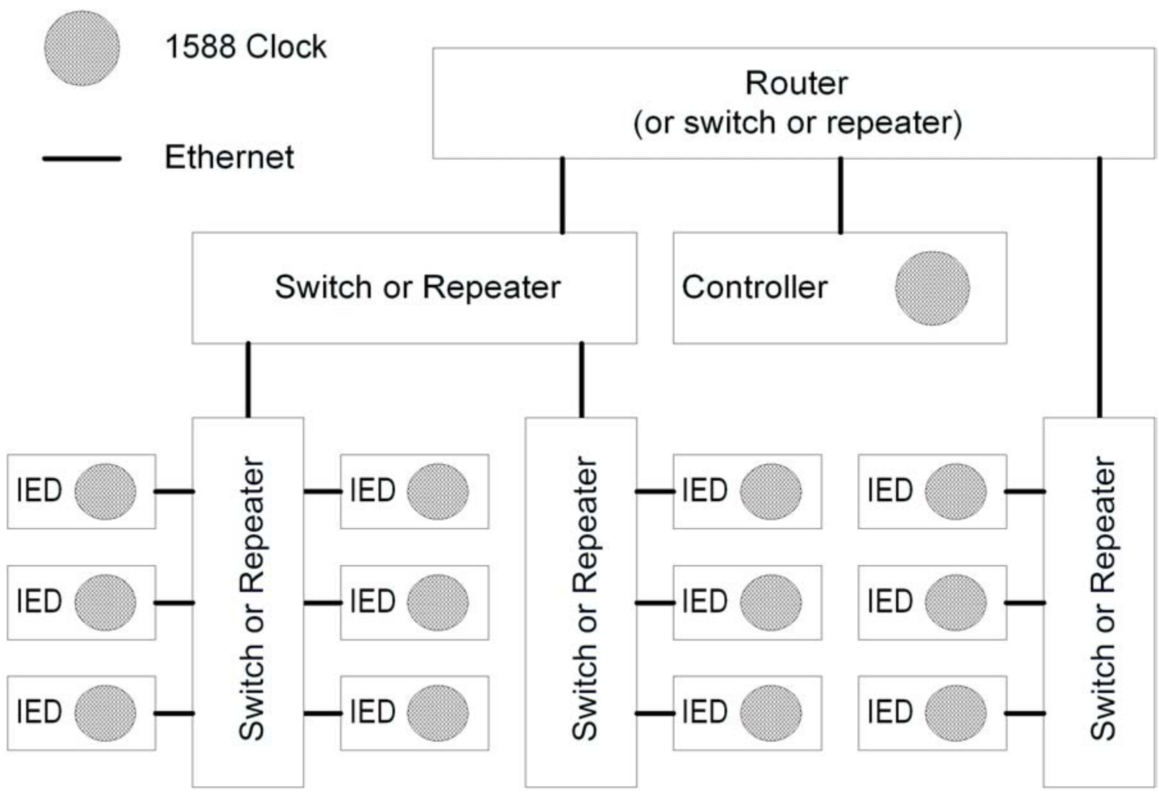

Figure 1: Time-based Ethernet Measurement and Control System

As noted, a common sense of time allows considerable decoupling of timing or synchronization requirements from questions of data management and communication. In many cases this can greatly simplify programming and reduce bandwidth and latency requirements for communication. This is illustrated by the following examples.

Data acquisition:
Systems like the one shown in Figure 1 are often used to acquire sensor data from a large number of sensors monitoring a physical system such as a substation. The data may be used for failure analysis, predictive diagnostics, or performance monitoring.
The presence of local real-time synchronized clocks allows the time stamp to be assigned at the source, that is by the IED, rather than by the controller with the data delivered as value time stamp pairs. This greatly simplifies the programming task and post collection analysis in that the temporal ordering of the acquired data is explicitly represented by the time stamp. The simplest systems will be ‘push’ systems in which each IED samples on a schedule tied to its local real-time clock, assigns a time stamp to each data point and then transmits the value time stamp pairs to the central controller for processing. The central controller’s function is reduced to one of data management, accepting, storing and analyzing the received data. The central controller need not be concerned with the details of the sampling process itself except for providing the specifications on sampling times to the IEDs.

Perhaps more importantly the network can be designed to correctly handle data throughput without excessive concern for latency or latency fluctuations since sample times are based on the local real-time clocks rather than message receipt. With clocks, it is also relatively easy to implement different or even adaptive sampling rates independently in each IED, not a pleasant task in a message or cyclic system. As the number of sensors increases, and for higher sampling rates and timing accuracy requirements the advantage of controlling the sampling and assigning time stamps within each IED using the local clock becomes more apparent. One of the more interesting examples of a large-scale, time-based data acquisition application is a particle detector for the 'OPERA' experiment at CERN [GIR]. This application required generating time stamped data on 72000 channels more or less simultaneously recording detected events with the resulting data aggregated using standard Ethernet network technology. Each channel contained a synchronized real-time clock and the data was aggregated in a hierarchical system much like that of Figure 1.

Fine grained fault analysis data acquisition:
The local caching of data in a time-based system allows a trade-off between local memory and communication bandwidth for certain classes of applications. For example, Figure 2 illustrates a data acquisition system designed to provide fine-grained temporal information about the status of devices over a time interval centered on the time of fault detection while delivering data at a lower rate for status monitoring during non fault operations.

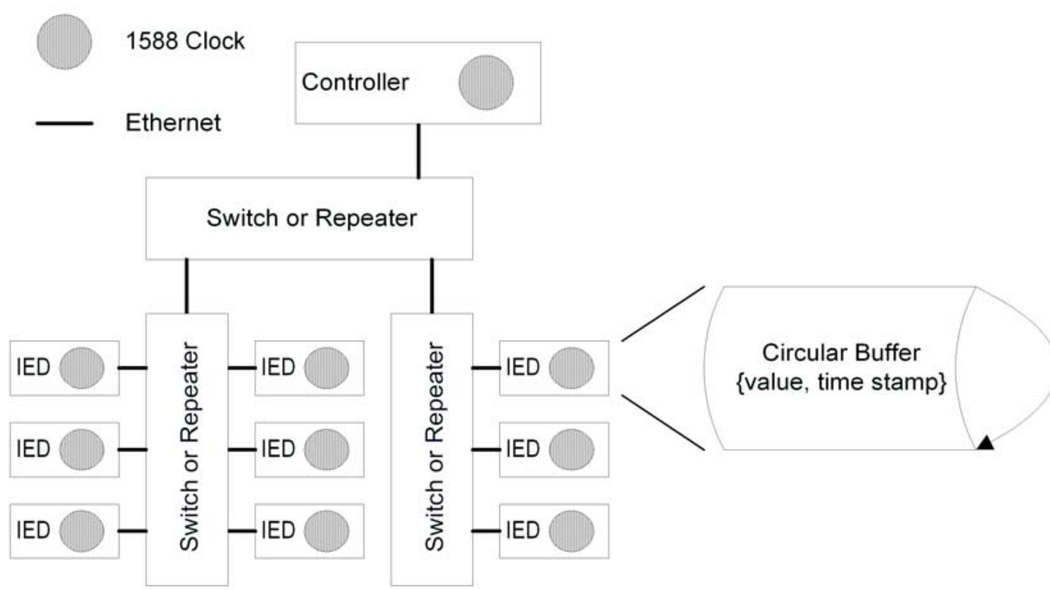

Figure 2: Fault timing measurement system

In this system, each sensor samples at the fine-grained interval required for the detailed data from that device and stores value time stamp pairs in a circular buffer. The sampling interval need not be the same for all devices. During normal operation, this data is decimated and delivered at longer sampling intervals.

Any device may detect a fault. When a fault is detected, the device sends a fault message containing the time of the fault to all participating devices. A multicast protocol (such as UDP/IP) is useful for this style of interaction. Devices receiving this fault message freeze their buffers in such a way as to retain the needed information before and after the fault time. Later, the controller, substation computer, or an engineering workstation at a remote site retrieves the data for post fault analysis. This ‘distributed logic analyzer’ style allows a trade-off between the amount of memory required in each device and the latency specification for delivering the fault message. The network bandwidth may be sized based on the non-fault data rates. By contrast, a system in which fine-grained data is continuously transmitted by all IEDs must be sized for much greater capacity.

Time-based control:
A similar advantage can be realized in certain classes of control applications where the synchronization of time across an entire system can serve as a means for synchronizing actions. This is illustrated in Figure 3.

In this case each IED is provided with a set of time-value scripts for various modes of operation. For example one of the IEDs in Figure 3 is preloaded with scripts for two normal modes of operation, A and B, and an emergency mode. The start-up script for mode A shows that the IED is to increase the value of some variable x from 0 at a time t0 to 1 over a 2 millisecond period and then shift to a normal mode. The time t0 is a relative time to be supplied by the controller to initiate the sequence. This technique allows each IED to operate autonomously once it receives the initiation message containing the ‘command’ and the ‘start time’. The only requirement to insure that the actions of all IEDs are properly synchronized is to insure that the command message reaches all IEDs before the actual starting time. This is a much easier specification to meet than implementing synchronization by requiring that the message reach all IEDs at the starting time. The technique illustrated in Figure 3 allows more robust systems to be built by using commitment protocols to ensure that all IEDs have the command message before allowing the system to proceed. If the commitment protocol does not complete by the starting time, IEDs could be programmed to ignore the command or take any other pre-programmed action such as an emergency procedure.

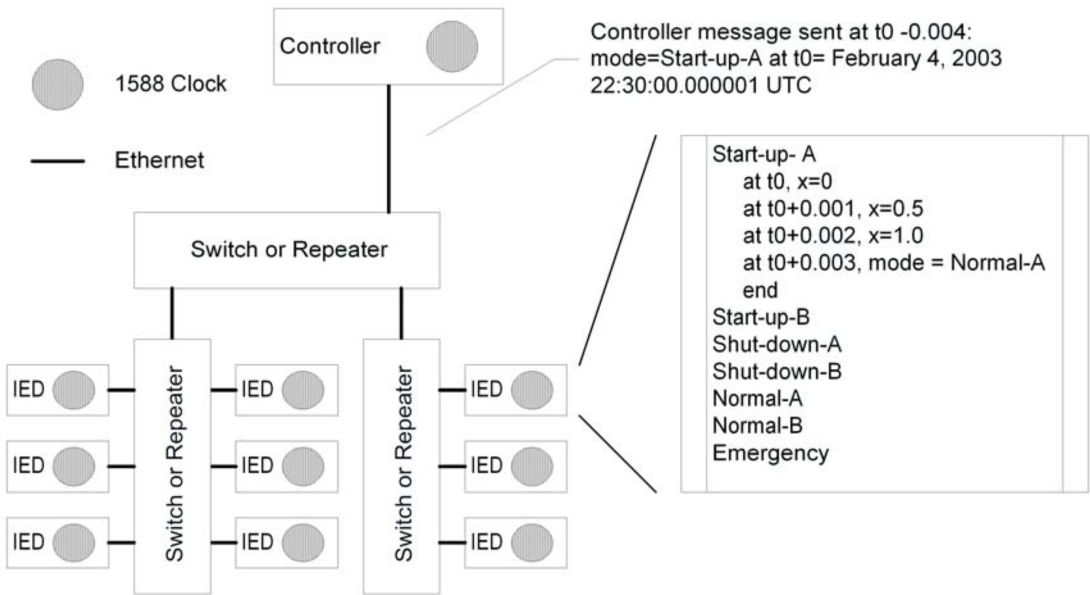

Figure 3: Time-based control system

There are many variations on this scheme that have found use in other domains such as motion control. For example, there are systems characterized by action time-value trajectories that follow pre-determined models, such as shown in the example in Figure 3, but must be corrected in real time based on some measurement. In this case, the execution of the models would be started as shown and the measurements delivered in real-time and processed by the individual IEDs. In many cases, the update corrections will represent small deviations from the model and can use longer sampling intervals to maintain the same accuracy than would be required for explicit point-by-point control using systems not based on a global sense of time.

Applications in the power industry

The power system infrastructure along with the telecommunications infrastructure represent the largest and most complex distributed systems built by man. By and large, these systems operate based on loosely coupled communications between local distributed components such as substations, generating plants, etc. To operate effectively, these systems share a global understanding of topology and time. Wide area timing is most effectively established using the global positioning system (GPS) maintained by the Department of Defense. Properly implemented, the GPS system will allow a global sense of time to be implemented with accuracy well below 100 ns. As described later, IEEE 1588 provides a method to synchronize local clocks to this accuracy as well.

Many of the techniques described earlier are already in place in various portions of the power system. Most if not all IEDs contain a clock. Today these clocks are synchronized within a site via some sort of timing bus. As in other industries, special purpose and proprietary communication networks, buses and protocols are being replaced by Ethernet based LANs. This trend will allow increased use of the techniques outlined and will enable more robust and easier to configure and maintain systems since the timing is decoupled from communication latency and fluctuation. Even greater efficiency and cost savings may be obtained by using these LANs to synchronize the clocks in the IEDs. Properly implemented, local clocks can actually be synchronized over the LAN to the necessary accuracy with much less communication bandwidth than required on a time bus distribution system. Local clocks can also be implemented with good holdover characteristics in the event of communication failure, thus allowing better implementation of emergency recovery strategies than if these strategies depended on a separate time distribution system.

Some obvious specific areas of application are fault diagnostics. The monitoring of the status of substation equipment for post fault analysis is a good example. The relative, or absolute timing of breaker closures, phase slippage, voltage spikes, etc. can be recorded and time stamped as described in connection with Figure 2.

There are some very interesting studies of large-scale phenomena in power systems [Lall]. System calculations based on the use of synchronized phasor measurement for various purposes have been well documented, [Pha], and new and more efficient algorithms are being developed, [Yang]. For accurate analysis using phasors, the protection and control systems collecting the data will depend on a common sense of time accurate to one microsecond, [Sch].

Within one substation, it has been shown that the function of circuit breaker closing after synchronism check can be accomplished with distributed voltage measurements. That is, the bus and line side voltages (magnitude, angle, and frequency) may be measured by different IEDs, and their data transferred over the LAN to a separate IED responsible for the reclosing function. This application requires the diverse IEDs to be synchronized to a common time base with an accuracy of ± 10 µs. See IEEE PC37.115 Annex B for a complete description, [PC37].

Overview of IEEE 1588

The IEEE 1588 standard specifies a protocol for synchronizing real-time clocks in a networked system of distributed components. The standard is designed to be applied in measurement and control applications typically found in electronic test, manufacturing, industrial automation, motion control, robotics, etc. and in local installations found in the power, telecommunications and similar fields.

The standard is optimized for:

1) Relatively compact systems of perhaps a few sub-nets such as might exist in a power substation, or in a generating plant.
2) Minimal use of network bandwidth, node computing and memory resources. This is to allow minimal interference with the other communication and computing tasks of the system and individual devices.
3) Low administration overhead to enable simple installation and replacement of devices using IEEE 1588 for synchronization.

4) Low-end and low-cost devices to allow even the simplest components in a power system to implement the protocol.

IEEE 1588 is designed to use networks supporting multicast communications including but not limited to Ethernet. Prototype implementations of IEEE 1588 have been tested on 10/100 BaseT Ethernet and on LonTalk™ networks.

IEEE 1588 is designed to seamlessly support heterogeneous systems containing clocks with a range of inherent resolutions, stability and accuracy. Synchronization accuracy is determined primarily by the capabilities of the individual clocks and, depending on the specific network technology, on the topology and implementation of network components.

The body of the standard specifies the message protocols, state machines, and the necessary characterization of clocks and other network components. For each target network it is expected that an annex to the standard body will be generated to specify network specific elements in particular the mapping of IEEE 1588 messages into the network specific on-the-wire format. Since it is expected that 10/100 BaseT or Base Fx Ethernet will be widely used in IEEE 1588 systems, the standards working group included a Normative Annex for Ethernet. The remainder of this discussion will use Ethernet as the example whenever network specific issues are discussed.

Figure 4 shows a typical distributed Ethernet based system in which each component includes a clock synchronized using IEEE 1588. Other networks will be similar, although they may not make use of switches and routers.

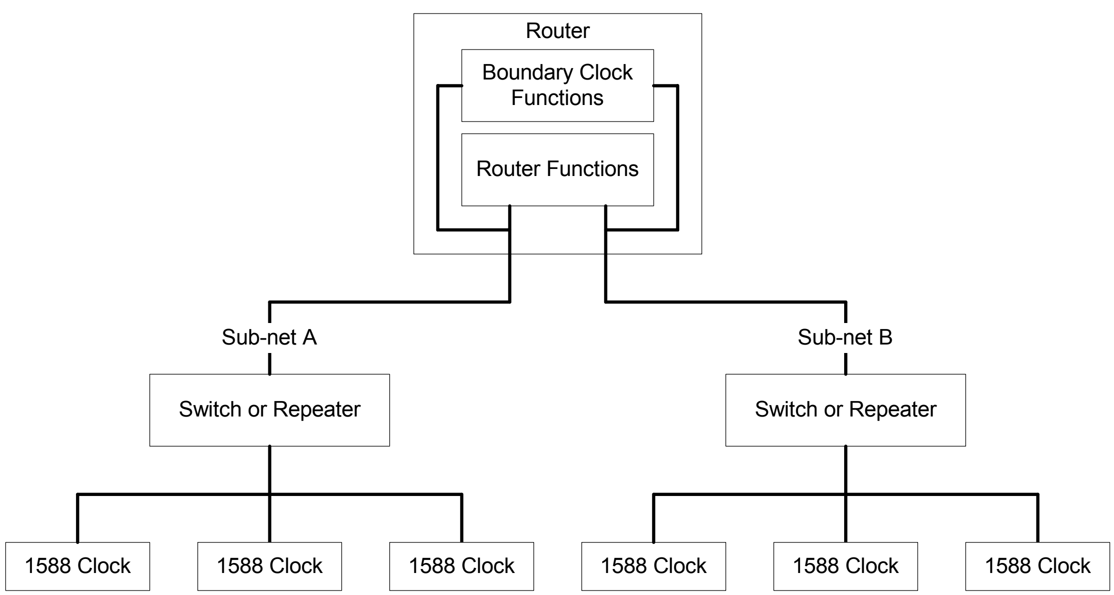

Figure 4: Multi-sub-net system including IEEE 1588 synchronized clocks

The system consists of two sub-nets ‘A’ and ‘B’ defined by the router. Each sub-net consists of several 1588 clocks, embedded in some component such as a controller, sensor, or another IED communicating with its peers in the sub-net via a switch or repeater. A very simple system might consist of a single sub-net.

As will be seen, Ethernet network components such as repeaters, switches and routers introduce considerable fluctuations in transmission latency that can degrade synchronization accuracy. Statistical techniques can reduce these fluctuations to acceptable levels for repeaters and, with proper care in network and traffic design, for switches.

This is not possible with routers which use extensive store and forward queuing. IEEE 1588 provides a ‘transfer clock’ mechanism to eliminate router fluctuations. A router implementing this mechanism contains two functional components: a) the normal routing functions allowing the router to establish sub-nets according to the underlying communication protocol, and b) IEEE 1588 defined boundary clock functions. The boundary clock functions remove the fluctuations in timing that would otherwise be introduced by the router functions. The boundary clock mechanism may also be implemented in switches to eliminate the effects of latency fluctuations in these devices.

IEEE 1588 uses a hierarchical master-slave protocol for synchronizing clocks. Typically, the 1588 protocol will select the ‘best’ 1588 clock in the system, termed the grandmaster clock as the root of this hierarchy. Within each sub-net, the protocol selects the ‘best’ clock of the sub-net to serve as the master clock of the sub-net. Within a sub-net, all 1588 clocks synchronize to the sub-net master that in turn synchronizes with the grandmaster. In a single sub-net system, the master and grandmaster are one and the same. In a system containing multiple boundary clocks, there is a hierarchy of masters with the grandmaster at the root. In all cases, the ‘best’ clock is determined by comparing inherent stability, accuracy, resolution, and other descriptors defined by IEEE 1588 along with network topology information. The topology information is deduced by the protocol and requires no commissioning, which allows the selection of the grandmaster and master clocks to be administration free under normal circumstances. IEEE 1588 does provide management messages that allow a specific set of clocks to be preferred in this selection process, if required by the application.

The time base established by the protocol will be the time base of the grandmaster clock. If the application requires that this time base be UTC (coordinated universal time), the grandmaster clock can be easily synchronized to a recognized source of UTC, for example the global positioning system (GPS) maintained by the US Department of Defense. If less absolute accuracy is needed, the grandmaster clock may be set manually using a 1588 defined management message. In this case, the clocks in all the slave IEDs are still precisely synchronized to the common time base established by the grandmaster clock.

Synchronization is achieved by master clocks periodically sending timing messages to their slaves. These timing messages are time stamped by both the master and the slave as close to the network as possible. For the greatest accuracy the master sends a second message to the slaves containing the precise time the master observed the timing message entering the network at the location of the master. Less frequently, the process is reversed, with slaves sending timing messages to their masters, to allow automatic calibration for communication latency between the clocks. On average, the 1588 protocol typically requires about 1 packet per second on the network. Minimal computing and memory resources are required in nodes hosting a 1588 clock, allowing implementation in relatively simple devices.

Some indication of the synchronization accuracy to be expected is illustrated in Figure 5 and Figure 6. This data was measured on two clocks implementing IEEE 1588 in a 10BaseT Ethernet environment. Figure 5 is a histogram of the time differences between the seconds transitions of two clocks communicating via a single HP J4090A Ethernet 10BaseT repeater. This prototype IEEE 1588 implementation produced synchronization accuracy with a mean of 22 ns and a standard deviation of 99 ns for this configuration.

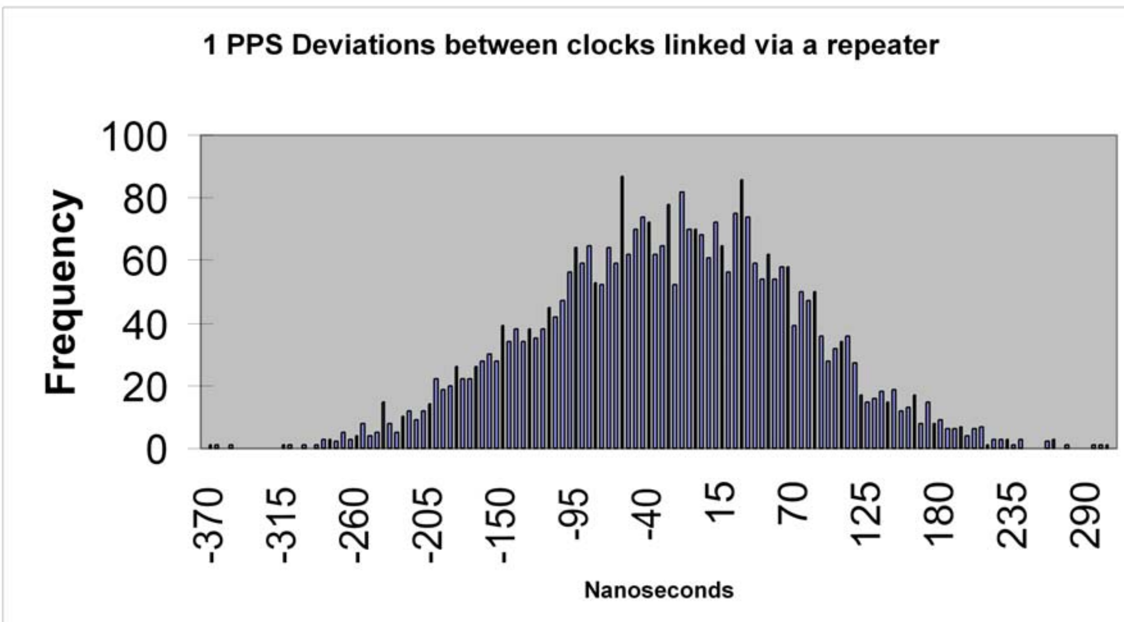

Figure 5: Synchronization deviations between two clocks communicating via a repeater

Network switches introduce significant latency fluctuations due to queuing. Figure 6 is a histogram of the time differences between the seconds transitions of two clocks communicating via a single, lightly loaded, HP J4121A Ethernet switch. This prototype IEEE 1588 implementation produced synchronization accuracy with a mean of 49 ns and a standard deviation of 233 ns for this configuration.

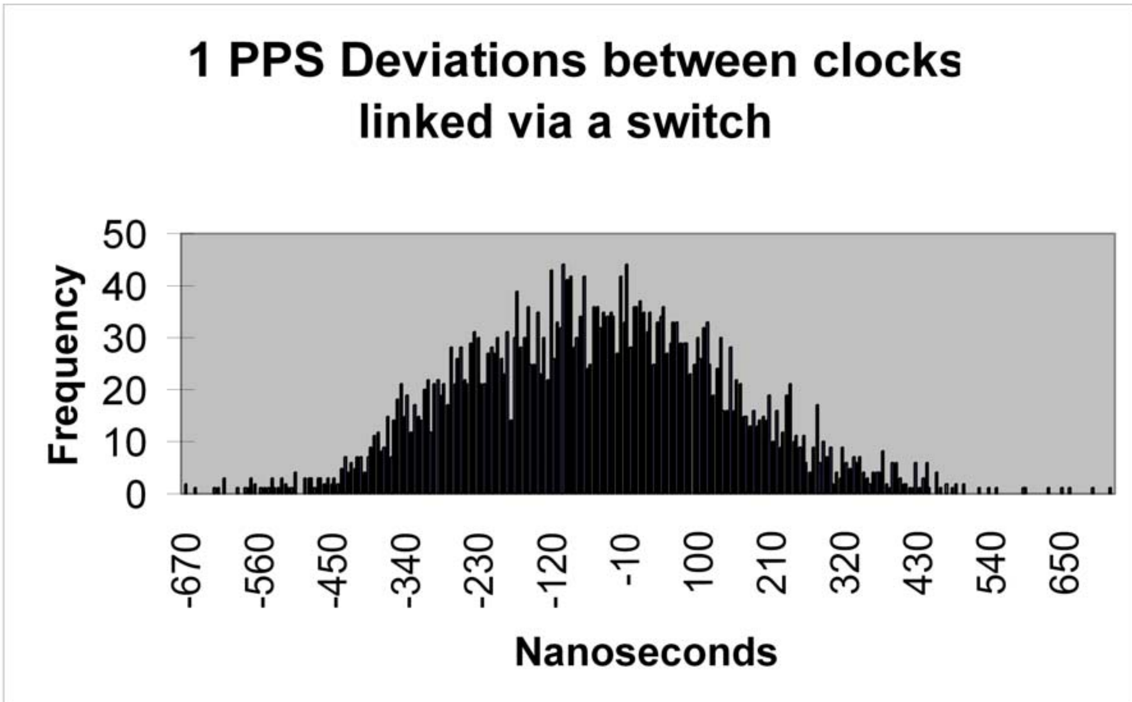

Figure 6: Synchronization deviations between two clocks communicating via a switch

Switches produce larger fluctuations than repeaters as evidenced by the degradation in the mean and standard deviation between the repeater, Figure 5, and the switch, Figure 6. Switch fluctuations can be greatly reduced by careful network traffic design and the use of quality of service features implemented on modern Ethernet switches, [MOLD]. It is also possible to design switches incorporating IEEE 1588 boundary clocks.

Synchronization below the microsecond level is most readily obtained using hardware assist techniques referenced in the standard. For accuracies in the range of tens of microseconds or more, it is possible to utilize software-only implementations although these will require interrupt driven or kernel level code. The hardware assist techniques are very simple and can easily be implemented in a small FPGA. In Ethernet the hardware assist operates at the MII interface of the PHY chip and requires no hardware or software modification of the Ethernet protocol stack. In many cases this is preferable to the use of interrupt or kernel level code that may complicate other applications executing in the IED unless careful programming practices are followed.

Conclusions:

The use of synchronized clocks in the components of distributed systems is well established in many aspects of the general computing and network environment. Many of these techniques are applicable to problems of measurement and control found in power systems and other industrial applications. When adequate synchronization accuracy is achieved, time-based systems have the potential of producing more robust, and easier to implement systems. IEEE 1588 is easily implemented in a wide range of devices. Depending on the required synchronization accuracy engineering tradeoffs are possible between pure software implementations and implementations using inexpensive hardware assist techniques.

IEEE 1588 is a new standard designed to synchronize clocks in environments found in the power industry, industrial automation, etc. IEEE 1588 has passed ballot and was approved by the IEEE Standards Board Review Committee at their September 12, 2002 meeting. It is currently in the publication process with publication expected early in 2003.

Further technical, application, and implementation details along with the latest information on the standard and directions for obtaining a copy from the IEEE are found on the 1588 web site [1588].

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[PC37]: PC37.115 Annex B Synch Check to Close Breaker (informative)

[1344]: See IEEE 1344-1995 – Standard for Synchrophasors for Power Systems

[1588]: See 'IEEE 1588 Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems' at http://ieee1588.nist.gov